

PLASMA THEORY AND SIMULATION RESEARCH

Final Technical Report *
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Berkeley, CA 94720

1990



ABSTRACT

The Berkeley Plasma Theory and Simulation Group has enjoyed the support of the Office of Naval Research since mid-1977, first on Contract No. N00014-44-C-0578 until mid-1985, and then on Contract No. N00014-85-K-0809 until 31 December 1989. This abstract covers highlights on the latter contract (1985-1989).

Our research group uses both theory and simulation as tools in order to increase the understanding of instabilities, heating, diffusion, transport and other phenomena in plasmas. We also work on the improvement of simulation, both theoretically and practically. Our focus has been more and more on the plasma edge (the "sheath"), interactions with boundaries, leading to simulations of whole devices.

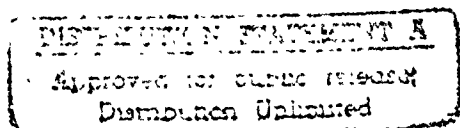
I. INTRODUCTION

Modern simulations have benefited greatly by improvements in numerical techniques, programming, and, of course, by much faster computers. Currently there are codes in use which are multidimensional, electromagnetic, and relativistic; these codes use realistic (close to laboratory and space) boundary conditions, with particle injection and collection. Many of the techniques for particle simulation were developed for fusion plasma applications, following both electrons and ions, with some attention to boundaries. In addition, there are now many applications to electron devices, such as klystrons, magnetrons, traveling-wave tubes, gyrotrons, accelerators, free electron lasers, and vircators; some of these codes are very large, say typically of 40,000 lines, usually run by groups of professionals. Applications to space plasmas are growing rapidly.

The beauty and quality of many-particle simulations comes from a combination of properties, such as:

- (a) working from first principles, using the Newton-Lorentz equation of motion to move particles, using Maxwell's equations to solve for the fields;
- (b) fields, potentials, currents and densities as functions of time and space (t, x) ; in addition, particle simulations can provide velocity distributions at (x, t) as well as Fourier decompositions in (x, t) ;
- (c) being fully nonlinear, that is, not restricted to relatively small amplitudes (although well used to verify linear theory), hence capable of following growth in (x, t) from linear through large amplitudes (e.g., saturation of amplifiers or instabilities);
- (d) complete accounting for spatial anisotropies and inhomogeneities;
- (e) ability to employ real boundaries with emission, absorption, reflection, surface charges and currents;
- (f) addition of Monte Carlo collisions between the charged particles and the neutrals, allowing self-consistent simulations of gas discharges (RF, DC, ECR, etc.)

* Also done under the titles "Plasma Instabilities and Nonequilibrium Processes" and "Plasma-Sheath-Surface Dynamics" ONR Contract No. N00014-85-K-0809



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Simulations are used to complement both theory and experiment, and to stand on their own. In the former, simulations are widely used by theoreticians in verifying linear and nonlinear theory, adding feedback for improvement in theory; simulations are useful to experimentalists in complementing explanations that they have obtained from their observations. In addition, simulations have proven very useful as a tool for exploration into new parameters, ahead of doing the comparable theory or experiments. Simulations have also been a tool for discovery, trying out new ideas, or (very importantly!) recognizing new and unexpected behavior. For example, we can say a great deal now about RF discharges, such as J E time and space resolved for electrons and ions, to show where the power goes as pressure changes, etc. The lesson is that particle simulations are both an asset to theory and experiment and have a role of their own.

II. SPECIFIC RESULTS

We have reported our results in Quarterly Progress Reports for many years. The sum total of these QPR's and journal publications over the July, 1985, to December 1989 period of ONR support is about five inches thick. We have chosen to provide a list of the titles of articles, reports and talks, with some comments on the publications of our group (16 articles, 24 reports, 64 talks, 1 workshop). ONR provides on the order of half the support of the group; that is, there is joint support for many of the published results. Our report is by year, highlighting work supported primarily by ONR.

1985

The Lawson article is unique, showing how to integrate the Vlasov equation in $f(x,v,t)$ when f has steep edge in (x,v) space. This is done by adding in a fake f to make total f smooth, but then ignoring the fake f in the potential solver. Comparisons with full particle dynamics are very good.

The Crystal-Kuhn article on the Pierce Diode is one of a series on such, adding more physics than done elsewhere (more to come).

Various talks presented our initial results on simulating bounded plasmas (whole devices).

1986

The Kuhn and Horhager work is from our occasional colleague S. Kuhn (Innsbruck) but part of our series on the Pierce Diode. Here, the interest is in stability as affected by R, L, C, elements in the external circuit. This is echoed in the Crystal and Kuhn talk.

The Theilhaber and Birdsall talk is the initial presentation of our 2d studies of surface waves in magnetized plasma sheaths, a milestone. (See 1989)

The Workshop was set up to draw attention to "bounded plasmas" per se, (as opposed to the plasma bulk, away from real boundaries). The response was excellent, with very good exchange of information.

1987

Kim's double layer article was a very neat, compact treatment, again part of a series of articles and simulations.

Lawson's "bounded plasma" report is the best exposition yet of such simulations, finally published in 1989.

The Theilhaber reports and talks are more introduction to the magnetized sheath in 2d.

Again, more Pierce Diode reports.

The Schwager talks are our early fully bounded source sheath and collector sheath simulations, with excellent checks with analytic results.

1988

Finally, the Theilhaber Kelvin-Helmholtz instability and vortex theory and simulation report is out, in detail.

The Schwager reports on the two sheaths are also out.

Birdsall receives the first IEEE Plasma Science and Applications Award and presents a talk on serendipity.

The first presentation of our RF discharge results is made by Morey et al. (at APS/DPP) displaying what is to become our PIC-MCC codes, adding Monte-Carlo collisions between charged particles and neutrals, a milestone in simulating weakly ionized gases (which means most laboratory and industrial plasmas).

1989

The Kelvin-Helmholtz instability in the magnetized sheath is now published in November Physics of Fluids, showing vertex formation and subsequent Bohm diffusion. This milestone had earlier presentations.

Again more presentations were made on our RF discharge results now showing considerable detail of interest to the plasma-assisted materials processing community (e.g. semiconductor etching, deposition and sputtering). The Alves et al. talk was the first simulation on asymmetric-electrode-RF discharges, coming very close to the analytic model of our colleague Professor M. A. Lieberman.

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Publications on
BOUNDED-PLASMA PHYSICS AND ENGINEERING 1985 - 1989

Our group began a transition into bounded plasma problems in 1981. Our new objective is to understand the dynamics of plasma sheaths at walls in terms of equilibrium, stability and transport. We also study other large potentials in plasmas, such as double layers and thermal barriers. The list here reflects the transition, a learning experience, starting with reports and talks, maturing into journal articles. Major support comes from DOE and ONR, plus help from Varian Associates-MICRO and Hughes.



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Statement "A" per telecon Dr. Charles Roberson. ONR/Code 1112AI

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1985

Book

C.K. Birdsall, A.B. Langdon, *Plasma Physics via Computer Simulation*, McGraw-Hill, New York. See especially Chapters 14, 15, 16 on bounded plasmas.

Journal Articles

W.S. Lawson, "A Method for Simulation of Vlasov Systems with Discontinuous Distribution Functions," *J. of Computational Physics*, 61 (1), p. 51, October 1985.

S. Ishiguro and T. Kamimura, "Double Layer Formation Caused by Contact Between Different Temperature Plasmas," *Physics of Fluids* 28 (7), pp. 2100-2105, July 1985.

T.L. Crystal and S. Kuhn, "Particle Simulations of the Low-alpha Pierce Diode," *Physics of Fluids* 28 (7), pp. 2116-2124, July 1985.

V.A. Thomas, V.M. Nevins, Y.J. Chen, "Simulation of the Ion-Beam-Driven Drift Instability in a Magnetic Trap. I" *Phys. Fluids* 28 (7), pp. 2235-2247 July 1985.

V.A. Thomas, V.M. Nevins, Y.J. Chen, "Simulation of the Ion-Beam-Driven Drift Instability in a Magnetic Trap. II" *Phys. Fluids* 28 (7) pp. 2248-2257, July 1985.

Reports

Bruce I. Cohen and Mark E. Stewart; Charles K. Birdsall, "Direct Implicit Particle Simulation of Tandem Mirrors," *LLNL Mirror Theory Monthly February 1985*.

C. K. Birdsall, T. L. Crystal, P. C. Gray and S. Kuhn, "Bounded Plasma Dynamics from Particle Simulations; Movie Script," Memo No. UCB/ERL M85/54, 2 July 1985, UC Berkeley.

Talks, Conference Proceedings

Sherwood Theory Conference, April 15-17, 1985, University of Wisconsin, Madison, Wisconsin:

L.A. Schwager and C.K. Birdsall, "A Model of the Plasma-Sheath Region Including Secondary Electron Emission and Ion Reflection."

Eleventh International Conference on Numerical Simulation of Plasma, Montreal, Quebec, Canada, 25-27 June 1985:

(1) C.K. Birdsall, W.S. Lawson, T. Crystal, S. Kuhn, N. Otani, I. Roth, and A.B. Langdon, "Problems of Bounded Particle Simulations and First Generation Solutions."

(2) B.I. Cohen, M.E. Stewart, and C.K. Birdsall, "Direct Implicit Particle Simulation of Tandem Mirror."

17th International Conference on Phenomena in Ionized Gases, Budapest, July 1985:

C.K. Birdsall, T.L. Crystal, P. Gray, and S. Kuhn, "Instability Of A Collisionless Single-Ended Plasma Device Operated In The Positive-Bias Electron-Rich Regime; From Simulations."

INTOR Specialists' Meeting On Impurity Control, IAEA Headquarters, Vienna, Austria:

C.K. Birdsall, "Boundary Conditions; Matching Plasma-Sheath-Wall." (invited paper)

Talks, Poster Papers

APS/Division of Plasma Physics Annual Meeting, Nov 4-8, 1985, San Diego, CA:

(1) B.I. Cohen, M.E. Stewart, R.P. Freis (LLNL), L.A. Strugala, and C.K. Birdsall, "Direct Implicit Particle Simulation of Tandem Mirrors."

(2) Wm. Lawson, P.C. Gray, E.A. Adler, and C.K. Birdsall, "A Simulation Study of Effects of Emission Noise in a Thermionic Diode."

(3) P.C. Gray, T.L. Crystal, S. Kuhn, and C.K. Birdsall, "Equilibrium Corrections for Electron Hole Filling: Simulation vs. Theory."

(4) L.A. Schwager and C.K. Birdsall, "A Model of the Plasma-Sheath Region Including Secondary Electron Emission and Ion Reflection."

(5) A. Wendt, P.C. Gray, H. Meuth, M.A. Lieberman and C.K. Birdsall, "Experimental and Simulation Study of Planar Magnetron Discharges."

(6) C.K. Birdsall, P.C. Gray and T.L. Crystal, "A Simulation Study of the Dependence of the Plasma-Sheath Impedance on Frequency."

(7) K. Theilhaber, G. Laval, D. Pesme, "Simulations of the Beam-Plasma Instability in the Turbulent-Trapping Regime"

1986

Journal Articles

Charles K. Birdsall, Niels F. Otani and Bruce I. Cohen, "Simulation of Plasma Dynamics Using Many Particles," *IEEE Electrotechnology Review* 2, pp. 43,44, 1986.

S. Kuhn and M. Hörhager, "External-circuit Effects on Pierce-Diode Stability Behavior," *J. Appl. Phys.* 60 (6), pp. 1952-1959, September 15, 1986.

ERL Reports

Niels F. Otani, "Saturation and Post-Saturation Behavior of the Alfvén Ion-Cyclotron Instability: A Simulation Study," University of California, Berkeley, Memorandum No. UCB/ERL M8615, February 19, 1986

Niels F. Otani, "Stabilizing Effects of Finite-Amplitude RF Waves on the Interchange Instability," University of California, Berkeley, Memorandum No. UCB/ERL M86/18, February 28, 1986

William S. Lawson, "Limits of Linear Response of a Vlasov Distribution," University of California, Berkeley, Memorandum No. UCB/ERL M86/44, June 3, 1986

Charles K. Birdsall, Niels F. Otani and Bruce I. Cohen, "Simulation of Plasma Dynamics Using Many Particles," University of California, Berkeley, Memorandum No. UCB/ERL M8647, June 3, 1986

K. Theilhaber, G. Laval and D. Pesme, "Numerical Simulations of Turbulent Trapping in the Weak Beam-Plasma Instability," University of California, Berkeley, Memorandum No. UCB/ERL M86/50, June 5, 1986

William S. Lawson, "Linear Magnetized Plasma Response to an Oblique Electrostatic Wave," University of California, Berkeley, Memorandum No. UCB/ERL M86/94, December 15, 1986.

Talks, Poster Papers

Sherwood Theory Conference. New York, N.Y. April 14-16, 1986.

N.F. Otani and B.I. Cohen, "Effect of Large-Amplitude Perpendicularly-Propagating RF Waves on the Interchange Instability."

APS Division of Plasma Physics Twenty-Eighth Annual Meeting, November 3-7, 1986, Baltimore, MD:

L.A. Schwager and C.K. Birdsall, "Transport across the Plasma-Wall Sheath with Secondary Electron Emission and Ion Reflection."

T.L. Crystal and S. Kuhn, "Pierce Diode Instability Simulations with External Inductance and Resistance."

S.E. Parker, C.K. Birdsall, and K. Theilhaber, "Electrostatic Effects on Confinement Outside the Separatrix of Field Reversed Configurations."

R.J. Procassini, C.K. Birdsall, and B.I. Cohen (LLNL), "Direct Implicit Particle Simulation of Tandem Mirrors."

K. Theilhaber and C.K. Birdsall, "Structure of the Crossed-Field Sheath." (with short movie)

Talks

C. K. Birdsall and the Plasma Theory and Simulation Group, "Planar Plasma Discharges: Simulations and Experiments," at Sandia National Labs, October 7, 1986.

C. K. Birdsall and Michael Lieberman, "Planar Plasma Discharges: Simulations and Experiments" at Varian Associates Technical Seminar, October 20, 1986.

Minicourse

Professor C.K. Birdsall presented the topic "Plasma Simulation Using Many Particles" at the *IEEE Minicourse on Generation of High-Power Microwaves, Millimeter-Waves, and Submillimeter Waves*, Saskatoon, Canada, May 21-23, 1986. His presentation was subsequently published as a chapter in the book, "High-Power Microwave Sources", edited by Profs. Igor Alexeff and Victor Granatstein. Artech, 1987.

Workshop

Bounded-Plasma Physics Workshop, University of California, Berkeley, September 22-23, 1986. See schedule following.

Bounded-Plasma Physics Workshop
University of California, Berkeley
September 22-23, 1986

Schedule of BPPW Presentations
Monday 22 September 1986

8:30 Registration and parking arrangements.
Coffee, tea, orange juice and rolls.

9:00 C.K. Birdsall (chairman). *Welcoming address and general information.*

C.K. Birdsall, (2)T.L. Crystal, P.C. Gray, S. Kuhn, and (1)Wm.S. Lawson *Introduction to PDW1 and Q-machine simulation; presentation of "The Movie".*

C.K. Birdsall, (1)T.L. Crystal, P.C. Gray, P. Krumm, (2)S. Kuhn, Wm.S. Lawson, M. Oertl, and N. Schupfer. *Trapped-electron effects on negative-bias d.c. states of a collisionless single-emitter plasma device: theory, simulation, and experiment.*

10:30 Coffee and posters of preceding talks.

11:15 K.S. Theilhaber. *Dynamics of the crossed-field sheath: a movie from the ES2 code.*

S. Parker. *Electrostatic potentials due to nonuniform magnetic fields.*

D.Hewett (LLNL).
Electromagnetic boundary conditions for implicit codes.

12:15 Lunch in Kerr Campus dining hall Building 10 (the great hall). Posters.

1:30 K.S. Theilhaber (chairman)

(1)T.L. Crystal, M. Hørhager, (2)S. Kuhn, and (3)Wm.S. Lawson.
*Theory and simulation of Pierce diode dynamics:
Linear and nonlinear features, plus nontrivial external circuit effects.*

C.K. Birdsall and P.C. Gray.
Small-amplitude impedance $Z(\omega)$ of a floating single-emitter plasma device.

2:30 Coffee and posters.

3:30 C.K. Birdsall, B.I. Cohen, and (1)R. Proccassini.
Efficient incorporation of Coulomb collisions in bounded-plasma simulations.

L.A. Schwager. *Transport in the plasma sheath region near a wall.*

S. Kuhn. *Integral-equation approaches to bounded-plasma physics.*

5:00 Coffee and posters.

6:30 Dinner in executive dining room Building 10, Kerr Campus.

Schedule of BPPW Presentations
Tuesday 23 September 1986

8:30 Coffee, tea, orange juice and rolls.

9:00 T.L. Crystal (chairman).

(1)C.K. Birdsall, and K.S. Theilhaber.
Source-sheath ion acceleration

P.C. Gray, (2)Wm.S. Lawson and (1)R.D. Pierce.
I — V curves of the Child-Langmuir electron diode from particle simulations.

10:30 Coffee and posters of preceding talks.

(1)A. Wendt, M.A. Lieberman and H. Meuth.
Theory of nonuniform plasma in a planar magnetron discharge

(1)J. Helmer and K. Doniger.
Ion diagnostics in a planar magnetron discharge.

12:15 Lunch
Posters.

1:30 S. Kuhn (chairman)

(1)T. Intrator (Wisconsin).
Some comments from experiments.

(1)Chris Goedde, M.A. Lieberman, A.J. Lichtenberg.
Stochastic electron heating in the sheaths of an RF discharge.

O. Buneman (Stanford).
Matching plasma radiation to free-space in spherical geometry using spherical harmonics (outward radiation only).

2:30 Coffee and posters.

3:30 O. Buneman (Stanford).

How to use a plasma boundary condition stated as $Z(\omega)$ in plasma simulation.

Panel discussion. M.A. Lieberman (chairman).

Concluding remarks from the steering committee...short!...and open discussion.
Where are we, where do we want to go, and what should we do next?

→ Should we have another BPPW in 1988?

Authors listed alphabetically
(1), (2) means talks split

1987

Journal Articles

K. Y. Kim, "Theory of Nonmonotonic Double Layers," *Phys. Fluids* 30, pp. 3686-3694, December 1987.

ERL Reports

William S. Lawson, "Computer Simulation of Bounded Plasma Systems," University of California, Berkeley, Memorandum No. UCB/ERL M87/14, March 5, 1987.

K. Theilhaber and C. K. Birdsall, "Vortex Dynamics and Transport to the Wall in a Crossed-Field Plasma Sheath," University of California, Berkeley, Memorandum No. UCB/ERL M87/18, April 10, 1987.

Kim Theilhaber, "ES2 User's Manual--Version 1," University of California, Berkeley, Memorandum No. UCB/ERL M87/23, May 11, 1987.

R. J. Procassini, C. K. Birdsall, E. C. Morse, and B. I. Cohen, "A Relativistic Monte Carlo Binary Collision Model for Use in Plasma Particle Simulation Codes," University of California, Berkeley, Memorandum No. UCB/ERL M87/24, May 14, 1987.

William S. Lawson, "Artificial Cooling Due to Quiet Injection in Bounded Plasma Particle Simulations," University of California, Berkeley, Memorandum No. UCB/ERL M87/34, May 21, 1987.

William S. Lawson, "The Pierce Diode with an External Circuit. I. Oscillations About Nonuniform Equilibria *Phys. Fluids B*, 1, July 1989, pp. 1483-1492.

William S. Lawson, "The Pierce Diode with an External Circuit. II. Chaotic Behavior," *Phys. Fluids B*, 1, July 1989, pp. 1493-1501.

Scott E. Parker, "Electrostatic Potential Formation Due to an Large Dip in the Magnetic Field with Application to FRC Confinement. University of California, Berkeley, Memorandum No. UCB/ERL M87/62, September 1987.

William S. Lawson, "The Pierce Diode with an External Circuit. III. Chaotic Behavior," University of California, Berkeley, Memorandum No. UCB/ERL M87/74, October 1987.

Talks, Conference Proceedings

At U.S./Japan Seminar: Effects of Electric Fields on Magnetic Confinement, January 22-24, 1987, University of California, Los Angeles:

K. S. Theilhaber and C. K. Birdsall, "Large Electric Fields in a Magnetized Plasma Sheath: Long-lived Vortices."

At Sherwood Controlled Fusion Theory Conference, April 6-8, 1987, San Diego, California:

K. Theilhaber, "Transport Induced by a Crossed-Field Sheath."

Richard J. Procassini and Charles K. Birdsall, "Performance and Optimization of Direct Implicit Time Integration Schemes for Use in Electrostatic Particle Simulation Codes."

Lou Ann Schwager, "Collector Sheath and Source Sheath in a Collisionless Finite Ion Temperature Plasma with Secondary Electron Emission and Ion Reflection at the Bounding Surface."

At IEEE International Conference on Plasma Science, June 1-3, 1987, Arlington, Va.:

K. Theilhaber and C. K. Birdsall, "Large Electric Fields in a Magnetized Plasma Sheath; Long-lived Vortices."

L. A. Schwager and C. K. Birdsall, "Potential Drop and Transport in a Bounded Plasma Including Secondary Electron Emission and Ion Reflection at the Collector."

At 12th Conference on Numerical Simulation of Plasmas, September 21-23, 1987, San Francisco, California:

A. Friedman, S.L. Ray, C.K. Birdsall, and S.E. Parker, "Particle-in-Cell Plasma Simulation with a Wide Range of Space and Time Scales."

S.E. Parker, "Numerical Error in Electron Orbits with Large $\omega_{ce} dt$."

B.I. Cohen, J.C. Cummings, R.J. Procassini, and C.K. Birdsall, "Direct Implicit Particle Simulation of Mirror Transport."

W.S. Lawson and T.L. Crystal, "Artificial Cooling Due to Quiet Injection in Particle Simulation of a Bounded Plasma."

Talks presented at US-Japan Workshop on Plasma Modeling with MHD and Particle Simulations, September 25-26, 1987, Napa, California. (Professor C.K. Birdsall was host, USA organizer):

A. Friedman, C.K. Birdsall, S.E. Parker, S.L. Ray, "Multi-Scale Particle Simulations."

K.S. Theilhaber, C.K. Birdsall, "Observing Kelvin-Helmholtz Mode Growth Near a Wall, Producing Long-Lived Vortices, in a Magnetized Plasma."

Invited Talk

At APS Division of Plasma Physics Twenty-Ninth Annual Meeting, November 2-6, 1987, San Diego, California:

K. Theilhaber, "Vortex Formation and Transport to the Wall in a Crossed-Field Sheath."

Talks, Poster Papers

Poster Papers at APS Division of Plasma Physics Twenty-Ninth Annual Meeting, November 2-6, 1987, San Diego, California:

C. K. Birdsall, K. S. Theilhaber, and S. Kuhn, "Ion Acceleration in a Plasma Source Sheath."

A. Friedman, S. L. Ray, S. E. Parker and C. K. Birdsall, "Prospects for Multi-Scale Particle-in-Cell Simulation of Plasmas."

Wm. S. Lawson, "Investigations of the Pierce Diode Strange Attractor." S. E. Parker, C.K. Birdsall, A. Friedman, and S. L. Ray, "Direct Implicit Particle Simulation of a Bounded Plasma System."

R. J. Procassini, J. C. Cummings, C. K. Birdsall, and B. I. Cohen, "Direct Implicit Particle Simulation of Simple Mirrors."

L. A. Schwager, "The Effect of Thermionic and Secondary Electron Emission at the Collector on Potential Drop and Transport Through the Plasma-Sheath Region."

1988

Journal Articles

Niels F. Otani and Bruce I. Cohen, "Effect of Large-Amplitude Perpendicularly Propagating Radio Frequency Waves on the Interchange Instability," *Phys. Fluids*, 31, pp. 158-176, January 1988.

ERL Reports

K. Theilhaber, "Vortex Formation and Particle Transport in a Cross-Field Plasma Sheath," University of California, Berkeley, Memorandum No. UCB/ERL M88/21, March 20, 1988.

Lou Ann Schwager and C. K. Birdsall, "Collector and Source Sheaths of a Finite Ion Temperature Plasma," University of California, Berkeley, Memorandum No. UCB/ERL M8/23, April 13, 1988.

Lou Ann Schwager, "Effects of Secondary Electron Emission on the Collector and Source Sheaths of a Finite Ion Temperature Plasma," University of California, Berkeley, Memorandum No. UCB/ERL M88/24, April 13, 1988.

Lou Ann Schwager, "Effects of Ion Reflection on the Collector and Source Sheaths of a Finite Ion Temperature Plasma," University of California, Berkeley, Memorandum No. UCB/ERL M88/25, April 13, 1988.

Talks, Conference Proceedings

ICRF/Edge Physics Workshop, March 30-April 1, 1988, Boulder, Colorado.

W. S. Lawson and C. K. Birdsall, "Undriven Plasma Wall Interaction Simulations, Showing Turbulence with and without an Initial Vacuum Gap."

W. S. Lawson and C. K. Birdsall, "Antenna Driven Plasma Wall Interaction Simulation, Showing Local Turbulence and About 3 Times Larger Flux to the Wall."

IEEE Conference on Plasma Sciences, June 6-8, 1988, Seattle, Washington.

C.K. Birdsall, "Serendipity is no accident, even in plasma research", Plasma Science and Applications Award acceptance address.

W. S. Lawson, M. A. Lieberman, and C. K. Birdsall, "Electron Dynamics of RF Driven Parallel Plane Reactor."

A. Friedman, S. L. Ray, C. K. Birdsall, and S. E. Parker, "Multi-Scale Particle-in-Cell Plasma Simulation: Timestep Control Criteria and some Tests."

APS Division of Plasma Physics annual meeting, Hollywood, Florida, October 31-November 4, 1988.

S.E. Parker, "A Proposed Particle-In-Cell Method for Modeling Small Angle Coulomb Collisions in Plasmas."

C.K. Birdsall, "Computer simulation of Plasma Response Near an RF Antenna."

I.J. Morey, R.W. Boswell, and C.K. Birdsall, "Particle Simulation of a Low Pressure RF Discharge."

Talk

C.K. Birdsall, "Plasma-Sheath-Surface Dynamics via Particle Simulations," June 9-10, 1988, at NSF Workshop on New Directions in Plasma Engineering.

Invited Talks (in Japan)

C.K. Birdsall, "Vortex formation and particle transport in a cross-field plasma sheath," (Co-author K. Theilhaber), September 26-27, 1988, at Plasma Sheath and Potential Formation Seminar, Sendai Japan.

C.K. Birdsall, "Plasma sheath small-signal RF impedances as obtained from simulations of a planar device," October 28, 1988, Seminar at Inst. Plasma Physics, Nagoya University, Japan.

C.K. Birdsall, "Source and collector sheaths in a bounded plasma device," (Co-author L.A. Schwager) and "The magnetized plasma sheath interacting self-consistently with an absorbing wall; Kelvin-Helmholtz instability growth with saturation as a dynamic steady state, producing Bohm diffusion," (Co-author K. Theilhaber), December 8, 1988, Inst. of Plasma Physics, Nagoya University, Japan. (The latter also presented at Hiroshima University a week later.)

C.K. Birdsall, "Hands-on demonstration on a personal computer of our periodic code ES1 and of our bounded code PDW1," (Co-author John Verboncoeur) December 9, 1988, Inst. of Plasma Physics, Nagoya University, Japan.

1989

Journal Articles

W.S. Lawson, "Particle Simulation of Bounded 1D Plasma Systems," *J. Comp. Physics*, 80 (2), February 1989, pp. 253-276.

K. Theilhaber and C.K. Birdsall, "Kelvin-Helmholtz Vortex Formation and Particle Transport in a Cross-Field Plasma Sheath," *Phys. Rev. Lett.*, 62, pp. 772-775, February 13, 1989.

B.I. Cohen, A.B. Langdon, D.W. Hewett (all at LLNL) and R.J. Procassini (here), "Performance and Optimization of Direct Implicit Particle Simulation", *J. Comp. Phys.*, 81, pp 151-168, March 1989

William S. Lawson, "The Pierce Diode with an External Circuit. I. Oscillations About Nonuniform Equilibria," *Phys. Fluids B*, 1, July 1989, pp 1483-1492.

William S. Lawson, "The Pierce Diode with an External Circuit. II. Chaotic Behavior," *Phys. Fluids B*, 1, July 1989, pp. 1493-1501.

K. Theilhaber and C.K. Birdsall, "Kelvin-Helmholtz Vortex Formation and Particle Transport in a Cross-Field Sheath I: Transient Behavior," *Phys. Fluids B*, 1, pp. 2244-2259, November 1989.

K. Theilhaber and C.K. Birdsall, "Kelvin-Helmholtz Vortex Formation and Particle Transport in a Cross-Field Sheath II: Steady State," *Phys. Fluids B*, 1, pp. 2260-2272, November 1989.

ERL Reports

J. Verboncoeur, "ES1 Reference Manual" (which is distributed with our PC disk, which is not included here - but free for the asking)

M.J. Gerver, S.E. Parker, and K. Theilhaber, "Analytic Solutions and Particle Simulations of Cross-Field Plasma Sheaths," Memo No. UCB/ERL M89/114, August 30, 1989.

I.J. Morey, and C.K. Birdsall, "Traveling-Wave-Tube Simulation: The IBC Code," Memo No. UCB/ERL M89/116, September 26, 1989.

S.E. Parker, and C.K. Birdsall, "Numerical Error in Electron Orbits with Large $\omega_{ce}\Delta t$," Memo No. UCB/ERL M89/136, December 20, 1989.

Talks, Conference Proceedings

At *Sherwood Theory Conference*, San Antonio, Texas, April 3-5, 1989:

W.S. Lawson and C.K. Birdsall, "Simulation of RF driven plasma edge."

S.E. Parker, C.K. Birdsall, A. Friedman, S.L. Ray, "Bounded multi-scale particle simulation: The sheath problem."

At *13th Conference on Numerical Simulation of Plasmas*, Santa Fe, NM, September 17-20, 1989

J.P. Verboncoeur, V. Vahedi, "WinGraphics: An Optimized Windowing Environment for Interactive Real-Time Simulations."

I.J. Morey, J.P. Verboncoeur, and V. Vahedi, "Bounded Plasma Device Simulation with PDW1, Including: External RLC Circuit, DC and RF Drive, and Collisional Processes."

I.J. Morey, and C.K. Birdsall, "The Traveling-Wave-Tube Code IBC."

M.V. Alves, V. Vahedi, and C.K. Birdsall, "PDC1: One-Dimensional Radial Code for a Cylindrical Plasma Device with an External RLC Circuit."

S.E. Parker, A. Friedman S.L. Ray, and C.K. Birdsall, "Multi-Scale Particle Simulation of Bounded Plasmas."

S.E. Parker, "A Particle-In-Cell Method for Modeling Small Angle Coulomb Collisions in Plasmas."

R.J. Procassini, C.K. Birdsall, B.I. Cohen, and Y. Matsuda, "Comparison of Particle-In-Cell and Fokker-Planck Methods as Applied to the Modeling of Auxiliary-Heated Mirror Plasmas."

Talks, Poster Papers

At *APS/Gaseous Electronics Conference Annual Meeting*, Palo Alto, CA, October 17-20, 1989

I.J. Morey, V. Vahedi, J.P. Verboncoeur, and M.A. Lieberman, "Particle Simulation Code for Modeling Processing Plasmas."

M.V. Alves, V. Vahedi, and C.K. Birdsall, "Cylindrical Simulations for RF Discharges and Plasma Immersion Ion Implantation."

At *APS/Division of Plasma Physics Annual Meeting*, Anaheim, November 13-17, 1989.

R.J. Procassini, C.K. Birdsall, and B.I. Cohen, "Particle Simulations of a Low-Recycling Divertor Scrape-Off Layer."

C.K. Birdsall, R.J. Procassini, and B.I. Cohen, "Particle Simulations of a High-Recycling Divertor Scrape-Off Layer."

R.J. Procassini, B.I. Cohen, Y. Matsuda, and C.K. Birdsall, "Modeling of Auxiliary-Heated Mirror Plasmas: A Comparison of Particle-In-Cell and Fokker-Planck Methods."

S.E. Parker, and R.J. Procassini, "Large Space and Time Scale Particle Simulation of Bounded Plasmas with a 'Logical Sheath'."

M.V. Alves, V. Vahedi, and C.K. Birdsall, "RF Plasma Processes in Cylindrical Models and Plasma Immersion Ion Implantation."

I.J. Morey, V. Vahedi, and J. Verboncoeur, "Particle Simulation Code for Modeling Processing Plasmas."

1990

Journal Articles

M. Surendra, D.B. Graves, and I.J. Morey, "Electron Heating in Low- Pressure RF Glow Discharges," *Appl. Phys. Lett.*, 56, pp. 1022-1024, March 12, 1990.

Lou Ann Schwager and C.K. Birdsall, "Collector and Source Sheaths of a Finite Ion Temperature Plasma," *Phys. Fluids B*, pp 1057-1068, May 1990.

I.J. Morey and C.K. Birdsall, "Traveling Wave-Tube Simulation: the IBC Code," *IEEE Trans. Plasma Sciences.*, pp. 482-489, June 1990.

J.K. Lee and C.K. Birdsall, "Particle Simulation of Drift Cyclotron Instability", *Japanese Journal of Applied Physics*, 29, October 1990.

R.J. Procassini, C.K. Birdsall, B.I. Cohen, "Particle Simulation of Collisional Transport in a Diverted Scrape-off Layer. Part I- The High-Recycling Regime", *Nucl. Fusion*. 30 pp.2329-2347, November 1990.

R.J. Procassini, C.K. Birdsall, E.C. Morse, "A Fully-Kinetic, Self-Consistent Particle Simulation Model of the Collisionless Plasma-Sheath Region," *Phys. Fluids B2*, pp. 3191-3205 December 1990.

A. Friedman, S.E. Parker, S.L. Ray, and C.K. Birdsall, "Multi-Scale Particle-In-Cell Plasma Simulation," accepted by *J. Comp. Physics*.

S.E. Parker, and C.K. Birdsall, "Numerical Error in Electron Orbits with Large $\omega_{ce} \Delta t$," accepted by *J. Comp. Physics*, April 1990.

S.E. Parker, R.J. Procassini, C.K. Birdsall, B.I. Cohen, "A Suitable Boundary Condition for Bounded Plasma Simulation without Sheath Resolution," accepted by *J. Comp. Physics*.

V. Vahedi, M.A. Lieberman, M.V. Alves, J.P. Verboncoeur, and C.K. Birdsall, "A One Dimensional Collisional Model for Plasma Immersion Ion Implantation," accepted by *J. Appl. Physics*.

M.V. Alves, M.A. Lieberman, V. Vahedi, and C.K. Birdsall, "Sheath Voltage Ratio for Asymmetric RF Discharges," accepted by *J. Appl. Physics*.

N.F. Otani, J-S Kim, C.K. Birdsall, B.I. Cohen, W. Nevins, N. Maron, "Elimination of Velocity Space Rings-and-Spokes Instabilities in Magnetized Electrostatic Particle Simulations of Plasmas," submitted to *J. Comp. Physics*, October 1989.

S.E. Parker, A. Friedman, S.L. Ray, and C.K. Birdsall, "Bounded Multi-Scale Plasma Simulation: Application to Sheath Problems," submitted to *J. Comp. Physics*.

J.P. Verboncoeur, M.V. Alves, V. Vahedi, "Simultaneous Potential and Circuit Solution for Bounded Particle Simulation Codes," submitted to *J. Comp. Physics* August 1990.

T.L. Crystal, P.C. Gray, W. S. Lawson, C.K. Birdsall, S.Kuhn, "Trapped Electron Effects on Time-Independent Negative-Bias States of a Collisionless Single-Emitter Plasma Device: Theory and Simulation," to appear in *Physics of Fluids B* 2, January 1991.

ERL Reports

M.V. Alves, M.A. Lieberman, V. Vahedi, and C.K. Birdsall, "Sheath Voltage Ratio for Asymmetric RF Discharges," Memo. No. UCB/ERL M90/56, June 21, 1990.

V. Vahedi, M.A. Lieberman, M.A. Alves, J.P. Verboncoeur, and C.K. Birdsall, "A One Dimensional Collisional Model for Plasma Immersion Ion Implantation," Memo. No. UCB/ERL M90/60, July 9, 1990.

J.P. Verboncoeur and V. Vahedi, "PDP1: Plasma Device Planar 1 Dimensional Bounded Electrostatic Code. Reference Manual," August 1990.

Conference Proceedings, Poster Papers

Sherwood Fusion Theory Conference, Williamsburg, VA, April 23-25, 1990:

R.J. Procassini, and C.K. Birdsall, "Particle Simulations of Transport in a Diverted Tokamak Scrape-Off Layer: The High-Recycling Regime."

Live demonstration in Plasma Visualization evening session 7-11pm April 24 of our bounded plasma PC codes. applications. (by Birdsall, Vahedi)

Microwave Power Tube Conference, Monterey, CA, May 7-9, 1990:

I.J. Morey, and C.K. Birdsall, "Traveling-Wave Tube Simulation; the IBC Code."

1990 IEEE International Conference on Plasma Science, Oakland, CA, May 21-23, 1990:

R.J. Procassini, C.K. Birdsall, B.I. Cohen, "Particle Simulations of Transport in a High-Recycling Divertor Scrape-Off Layer."

M.V. Alves, M.A. Lieberman, V. Vahedi, C.K. Birdsall, "Sheath Voltage Ratio For Asymmetric RF Discharges."

J.P. Verboncoeur, V. Vahedi, M.A. Lieberman, C.K. Birdsall, "Work Done And Energy Balance in RF Discharges."

V. Vahedi, M.A. Lieberman, M.A. Alves, J.P. Verboncoeur, C.K. Birdsall, "Collisional Model For Plasma Immersion Ion Implantation."

Workshop on High-Density Plasma Techniques and Processes for Integrated Circuit Fabrication, Burlingame, CA, September 11-12, 1990.

V. Vahedi, M.A. Lieberman, M.A. Alves, J.P. Verboncoeur, and C.K. Birdsall, "A One Dimensional Collisional Model For Plasma Immersion Ion Implantation."

V. Vahedi, J.P. Verboncoeur, M.A. Alves, and C.K. Birdsall, "Plasma Processing Via Computer Simulation."

43rd Annual Gaseous Electronics Conference, Urbana-Champaign, IL, October 16-19, 1990.

C.K. Birdsall, "Particle-In-Cell Combined with Monte Carlo Collisions-In Living Color." (Invited talk)

J.P. Verboncoeur, V. Vahedi, and C.K. Birdsall, "Power Deposition in Parallel Plate Discharges."

APS/Division of Plasma Physics, Cincinnati, OH, November 12-16, 1990.

S.E. Parker, and C.K. Birdsall, "Particle Transport due to Kelvin-Helmholtz Vortices and Small Scale Turbulence."

US-Japan Workshop on "Advanced Computer Simulation Techniques Applied to Plasmas and Fusion,"
UCLA, September 26-28, 1990.

V. Vahedi, J.P. Verboncoeur, M. Surendra, and C.K. Birdsall, "A Monte-Carlo Collision Model for the Particle-in-Cell Method."

Course

M.A. Lieberman and C.K. Birdsall, "Low Pressure Plasma Discharges Used in Semiconductor Processing", UC Extension, San Francisco, CA, May 23-25 1990, and Oxford, England, July 9-11, 1990.

Invited Talks

C.K. Birdsall, "Interactive Plasma Computer Experiments; Plasma Device Simulations on PC's and Workstations," January 16, 1990 at Naval Research Laboratory, Washington, D.C.

C.K. Birdsall, "Magnetized plasma sheath, with Kelvin-Helmholtz instability, vortices, Bohm-like diffusion", and "Computer experiments with bounded collisional plasmas on fast PC's, March 26-27, 1990, at University of Wisconsin, Madison, Wisconsin.

C.K. Birdsall, "Interactive Plasma Computer Experiments; Plasma Device Simulations on PC's and Workstations," June 1, 1990 Naval Post Graduate School, Monterey, CA.

C.K. Birdsall, "Particle-in-Cell combined with Monte-Carlo Collisions - In living color", *Gaseous Electronics Conference*, Univ. of Illinois, Champaign IL, October 16-19, 1990.